CONCEPTS FOR HIGH PRECISION TIME AND FREQUENCY TRANSFER BETWEEN EARTH AND SPACE CLOCKS

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ABSTRACT

Operation of new space fountain clocks now provides levels of accuracy and frequency stability approaching one part in 10^{16}. We offer some ideas for providing access to this accuracy and stability with Doppler canceling microwave techniques that employ coherent carrier phase. Corrections for relativistic effects will require continuous tracking of position and velocity at levels of precision that are now realistically expected from Global Positioning System which also provides time transfer capability to enable high precision orbit-to-orbit recovery of phase in the Doppler canceling system.

1. THE TIME TRANSFER CHALLENGE FROM NEW SPACE CLOCKS

We suggest that this challenge can be met with a microwave system based on the three-link Doppler-canceling system used in the 1976 Gravity Probe-A (GP-A) test of the Gravitational Red shift[1] (shown in Figure 1) operating with data from the Global Positioning System (GPS).

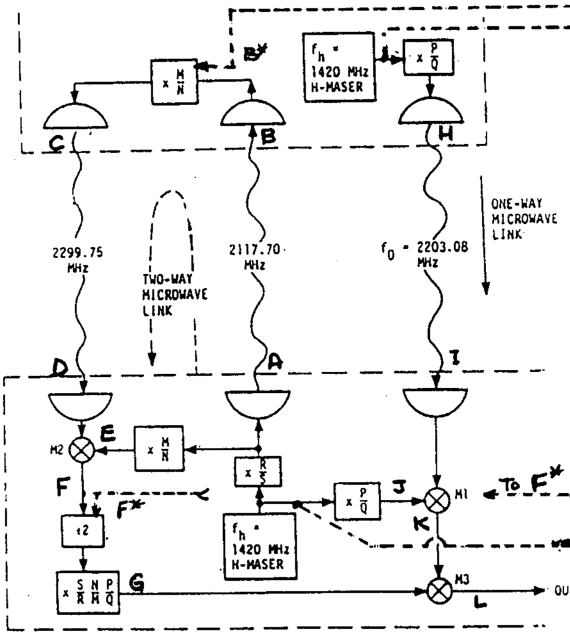
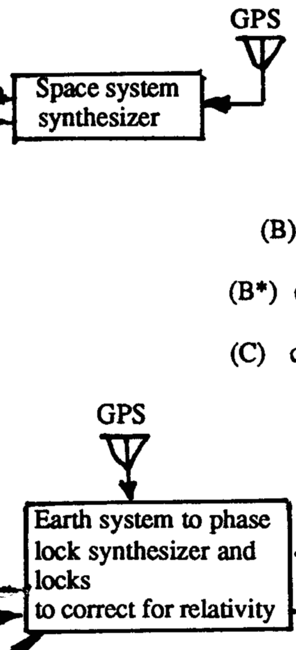


Figure 1 Schematic of the GP--A System

The GP-A Doppler canceling system makes real time measurements of the signal phase delay in the ray path by systematically subtracting one-half the phase delay from a separate two way path measurement from the phase delay in the one-way clock link. Here, we assume that all propagation effects in the up link and down link signal paths are reciprocal. Equation 1 describes the relativistic and gravitational frequency shifts that were involved in the GP-A test. For transferring time (phase) over extended intervals we must continuously integrate these frequency shifts over the interval of phase transfer to correct the measured elapsed phase.

$$\frac{f_s - f_e}{f_0} = \frac{(\phi_s - \phi_e)}{c^2} - \frac{|\vec{v}_e - \vec{v}_s|^2}{2c^2} - \frac{\vec{r}_{se} \cdot \vec{a}_e}{c^2} \quad \text{...........(1)}$$

Here the total frequency shift is $f_s - f_e$, and f_0 is the clock down link frequency. The Newtonian potential difference between the spacecraft and earth station is $(\phi_s - \phi_e)$, $\vec{v}_e$ and $\vec{v}_s$ are the velocities of the earth station and the spacecraft in an inertial frame. The vector distance between the spacecraft and earth station is r_{se} and a_e is the acceleration of the earth station owing to the earth's rotation. The first term in Equation 1 is the gravitational red shift. The second term is the second-order Doppler effect of special relativity and the third term is a non-relativistic effect from the acceleration of the earth station during the light time, r_{se}/c.



$\omega_s = 2\pi f_h$ space
$\omega_e = 2\pi f_h$ earth
* derived from GPS data
$\phi_r(t)$ are relativistic effects

(A) $\cos [\frac{R}{S} \omega_e t]$

(B) $\cos \frac{R}{S}[\omega_e(t + L(t)/c) + \phi_r(t)]$

(B*) $\cos \frac{R}{S}[\omega_s(t + L^*(t)/c) + \phi_r^*(t)]$

(C) $\cos \frac{M}{N}\frac{R}{S}[\omega_e(t + L(t)/c) + \phi_r(t)]$

(H) $\cos \frac{P}{Q}[\omega_s t + \phi_{arbitrary}]$

Corrected time
< ±68 ps. between
<< ± 6.8 ps.when locked

(E) $\cos \frac{M}{N}\frac{R}{S}\omega_e t$ (F) $\cos \frac{M}{N}\frac{R}{S}\omega_e 2L(t)/c$

(F*) $\cos \frac{M}{N}\frac{R}{S}\omega_e 2L^*(t)/c$ (G) $\cos \frac{P}{Q}\omega_e 2L(t)/c$

(D) $\cos [\frac{M}{N}\frac{R}{S}\omega_e(t + 2L(t)/c)]$ note: $\phi_r(t) = 0$

(I) $\cos \frac{P}{Q}[\omega_s (t + L(t)/c) + \phi_0 + \phi_r(t)]$ (J) $\cos \frac{P}{Q}\omega_e (t)$

(K) $\cos \frac{P}{Q}[(\omega_s - \omega_e)t + \omega_s L(t)/c] + \phi_0 + \phi_r(t)]$

(L) $\cos \frac{P}{Q}[(\omega_s - \omega_e)t + (\omega_s - \omega_e) L(t)/c] + \phi_0 + \phi_r(t)]$

Note: $(\omega_s - \omega_e)\, L(t)/c\ (\max) < \pm 7 \times 10^{-6}$ degrees. Predictions for the frequency shifts shown in Equation 1. will require continuous tracking of position and velocity. Velocity within 1 mm per second and space craft position within 0.5 meter are required for 1 part in 10^{16} accuracy in frequency prediction.

2. GPS SYSTEM PERFORMANCE

Tracking data at the required level of precision to support the performance of the new space clocks are now available from the GPS system[2] and can be sent, in near real time, to the earth stations for correcting time and frequency data. It is worth noting here that these frequency corrections at the 10^{-16} level imply confidence in a hundred-fold improvement in the results of the 1976 GP-A test.

The current use of high-quality data from a global network of GPS receivers has revolutionized high precision time and frequency transfer for users on the earth. This network consists of geodetic-quality GPS receivers, providing dual-frequency pseudo range and carrier phase observables. Data from about 35 globally distributed receivers are used in a daily grand solution. Parameters that are determined include receiver positions, GPS satellite orbits and time at receiver and satellite clocks. Solutions also include tropospheric delay, various parameters describing solid earth orientation and rotation, and ionospheric effects. Corrections for other effects include general and special relativity, solid-earth tides, and tidal loading[3]. The time transfer accuracy that has been obtained from these solutions is shown in Figure 2.

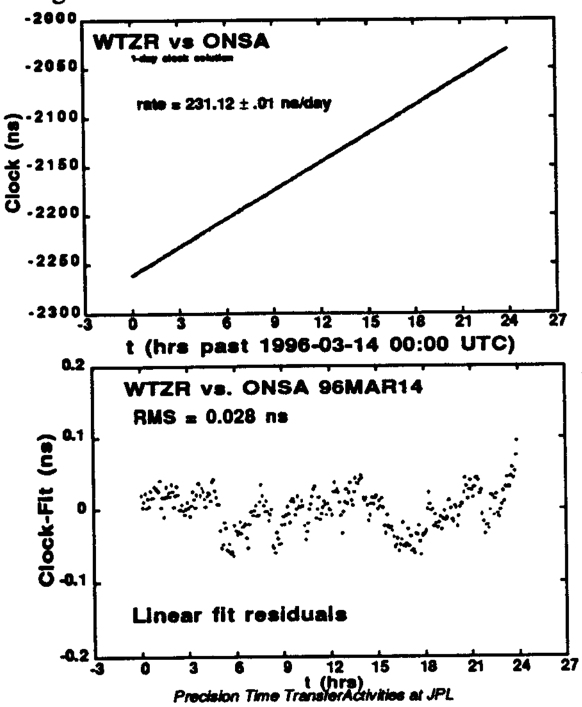


Figure 2 Linear Fits to JPL's GPS-based clock estimates for pairs of H-Masers worldwide show rms scatter of less than 30 picosec.

Extension of GPS time transfer between ground clocks to a clock on a space station requires resolution of an additional source of error. For transfer between earth stations, the position of each receiver is estimated as a single set of coordinates for each day. In the case of the International Space Station (ISS), a solution for its kinematic orbit must be found. Because uncalibrated forces act on the ISS, we cannot use a dynamic model, instead we will determine a series of trajectories. Recent studies[4] indicate that, with certain assumptions on satellite visibility and observable errors, one day frequency transfer between a clock on the Space Station and a set of clocks on earth can be made with precision of one part in 10^{15}.

The GPS time transfer process is continuous, and does not require mutual visibility between the space clock's receiver and a given ground site. The presence of a global network of ground receivers with continuous mutual visibility with the orbiting receiver allows transfer of precise timing information among all the receivers in the grand solution.

3. CORRECTIONS FOR IONOSPHERIC EFFECTS

Signals at the three different frequencies operating in the 1976 GP-A system had different ionospheric propagation delays. In the GP-A test, corrections for these effects were made by the choice of the signal frequencies[5]. The algorithm for removal of the $1/f^2$ ionospheric dispersion for such a system is:

$$f_{\text{clock downlink}} = f_{\text{uplink}} \sqrt{2} \left[1 + \frac{f^2_{\text{uplink}}}{f^2_{\text{downlink}}} \right]^{-1/2}$$

These frequencies were obtained with ratio synthesizers. The existing Unified S Band transponder system had turn-around ratio, M/N = 240/221 The uplink and downlink frequencies were generated by R/S (= 82/55) and P/Q (= 76/49) times the maser output frequency, f_h =1.420 GHz. These choices of frequencies reduced the $1/f^2$ component of the ionospheric frequency shift by a factor of 2.5 x 10^{-5} in the output. Note that signal reciprocity is only valid for the $1/f^2$ dispersion from the ionosphere. Higher-order 1/f terms[6], whose effects are small could still be significant at some future level of required precision. Operating at higher frequencies would further reduce ionospheric effects.

4. PHASE AND FREQUENCY TRANSFER WITH THE THREE LINK SYSTEM OPERATING WITH GPS

4.1 GP–A Mission Data

Figure 3 shows sections of the sine/cosine analog data taken during the two-hour near vertical GP-A mission. (The data used for data reduction were taken at 14 bits every 0.01 sec.)

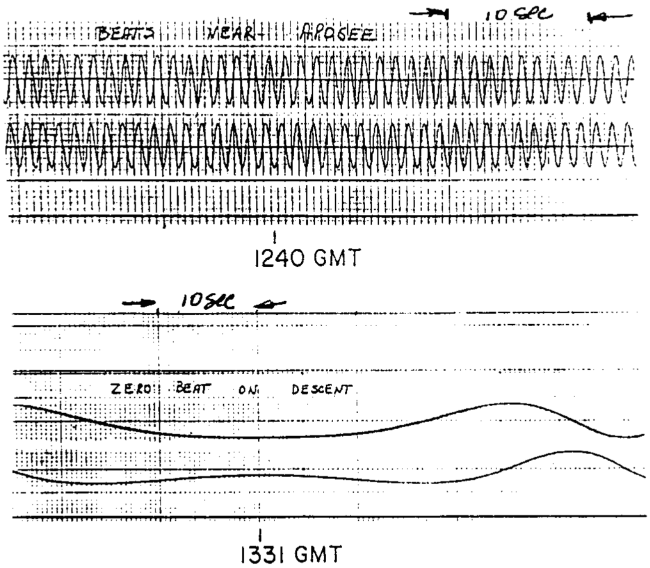


Figure 3 Analog data plots of apogee and zero beat output from Mixer M3 in Figure 1.

Here we see a segment of data where the first two terms in Equation 1 cancel each other during ascent and descent that illustrate the slow phase characteristics of the signal. If the mission had been in a 24 hour orbit and the data continuously corrected for the effects shown in Equation 1 (and with well matched clocks) the system would have continuously compared the phase of the space clock's signal with that of the earth based clock. Each cycle of phase observed in the output from the 2.2 GHz Doppler canceling system implies 454 picoseconds of time difference between the clocks. Assuming 1 part in 10^{16} fractional frequency stability between the earth and space clocks over one day, and correcting for gravitational and relativistic frequency corrections, the 2.2 GHz system would show about $\pm$ 6.8 degrees of phase difference over one day or $\pm$ 8.6 picoseconds of time difference. From the digitally recorded near zero-beat measurements made in 1976, and averaging for about 100 sec, we estimate we can measure this phase with a precision of about 1 degree or 1.26 picoseconds.

4.2 Orbit to Orbit Data Re acquisition and Performance with the Combined GPS and Three Link Doppler Canceling System

For a low-earth ~90 minute orbit, the question is how to reconnect the phase of the system from orbit-to-orbit and represent it as if it had not been interrupted. Relocking after an interruption simply restarts the clock phase comparison and again removes the new path delay. With the 90 min. orbit we expect to operate the microwave system for about 300 seconds at least once a day. Once relocked, we must reconnect the sine/cosine received phase as if it had not been interrupted. *This will require maintaining the locking conditions of the space and earth station ratio synthesizers shown in Figure 1.*

The GPS system will compare the relative frequency of the space and earth clocks within 1 part in 10^{15} over 1 day. If the elapsed relative phase difference in the clocks (corrected for relativistic gravitation) is less than one quarter cycle at S Band (454 picosec), the GPS data will unambiguously confirm that the cycle of phase in the recovered beat signal is correct.

Note that the principal limitation to the time transfer with the GPS system is from propagation delay effects, not from gravitational and relativistic corrections made from tracking information. The proposed Doppler canceling system will remove propagation effects by *direct real time measurement* and the GPS will provide data for relativistic and gravitational corrections providing time transfer with an estimated precision within a few picoseconds.

4.3 Maintaining Phase Coherence in the Ratio Transponders

Between periods of ground station interrogation we must maintain the phase relationship between up and down links in the M/N ratio transponder. For the 240/221 turn-around ratio, regaining lock after loss of an uplink signal involves a random choice of some 240 possible re-engagement phase angles. We can maintain this phase engagement between contacts by applying a signal to emulate the received uplink signal from the earth station during periods of no earth signal. Once the uplink signal diminishes below a certain level, this locally generated signal will maintain the lock of the space transponder until earth station contact is resumed. This signal will be continuously generated by the GPS system and include corrections for relativistic gravitational effects and the propagation distance between the earth and space stations (even through the center of the earth).

An alternative method is direct measurement of the relative input-to-output phase at each sysntesizer. This can be done by sending these measurements to a GPS receiver that has been modified to track unmodulated carrier.

A similar system will be used on the earth station to retain ratio synthesizer coherence between space station contacts.

5. A CONCEPTUAL SYSTEM

5.1 System Concept

The dotted lines at the right of Figure 1 show conceptual GPS additions to the system used in GP-A to retain ratio synthesizer phase and to correct for relativity. Signal phase at various points is indicated by letters.

During contact with space, all ratio synthesizers are locked to real signals. When the space station is out of sight of a ground station, or when, for any other reason there is no uplink, the space station, transponder will lock onto a GPS-derived signal that will serve to maintain the relative uplink-downlink lock phase constant until the uplink reappears. This system will provide a fail-safe feature for maintaining phase continuity between orbits and will consist of an SNR estimator, a selective AGC amplifier chain and a coupler that will gracefully substitute the GPS-derived signal in to the receiver input as the uplink signal fades. The output from mixer M3 will be sent to the earth station digital processor and corrected for relativistic gravity with GPS data. This will produce clock comparison data with a precision of a few picoseconds. During the periods of no contact as long as one day, the processor will apply relativistic phase and range distance corrections to predict the time difference between earth and space well within about 86 picoseconds. With the expected $1x10^{-16}$ frequency stability of the clocks, we can expect time data during contact to be within ± 6.8 degrees per day, well within the 68 degree prediction capability from GPS thus confirming that no 2π ambiguity is present in the phase data.

5.2 Transmitter Power Levels and Uplink and Downlink Antennas

Table 1 describes signal power levels and antenna configurations for the system.

	90^0 Elevation	20^0 Elevation
Ground Radiated Power	20 W	
Transmit Frequency	2200 MHz	
Ground Antenna Diameter	2 m	
Ground Antenna Efficiency	0.6	
Ground Antenna Gain	31.1 dB	
S/C Range	400 km	984 km
Space Loss	151.3 dB	159.1 dB
Receiving Antenna Gain	2.0 dB	-14.0
Polarization Loss	0.5 dB	
S/C Waveguide Loss	1 dB	
Total ISS Received Power	-77 dBm	-100 dBm

Table 1

It will be important to have as clear a transmission path as possible between the earth station antenna and the space station antenna. The earth station antenna will be steerable. In space, a fixed nadir-pointing flared open wave guide antenna mounted as low as possible and surrounded by a circular shield at least 1 meter in diameter should serve. Calibration of the signal phase at each of the three frequencies as a function of antenna viewing angle will be necessary as the three frequencies will not have the same phase centers. We understand that attitude of the ISS with respect to the line of sight to the earth stations will be available with a precision of 0.1 degree[7].

The present transponder requires about –100 dBm of signal power to maintain the 1 degree RMS of turnaround phase stability.

6. CONCLUSIONS

We have shown with data from a previuos experiment and with present technology that space-to earth-time transfer is possible to support the best available frequency standards. The essential feature is use of carrier phase to avoid effects of modulation that cause multipath problems. For low earth orbiting spacecraft we can cancel propagation phase delay by direct two-way measurement and subtracting, in real time, half of the two-way delay from the one-way timing signal.

Very low noise transponders operating with phase coherent ratio synthesizers have long been available. In the 1976 GP-A test, ratio transponders were used in both the earth and space stations to maintain completely coherent phase comparisons throughout the mission.

The initially engaged input/output phase of ratio synthesizers, established at the start of a period of time comparison, must be maintained between periods between subsequent contact to update the phase in these contacts. This phase condition can be preserved by operating the ratio synthesizers with signals derived from GPS to emulate, within less than π radians, the phase conditions expected between contacts. The expected GPS and clock performance should allow continued and unambiguous high precision time comparisons with contacts, spaced as long as one day apart.

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